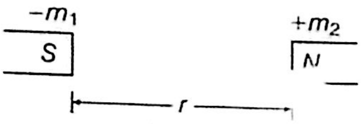
Magnetism and Matter(Revision notes)

[TOPIC 1] Magnetic Dipole and Magnetic Field Lines

A magnet is a material or an object that produces a magnetic field. The magnetic field is invisible but is responsible for most notable property of magnet.

1.1 Force Between Two Magnetic Poles

Magnitude of force acting between two magnetic poles is given by



$$\mathbf{F} = k\frac{m_1 m_2}{r^2}$$

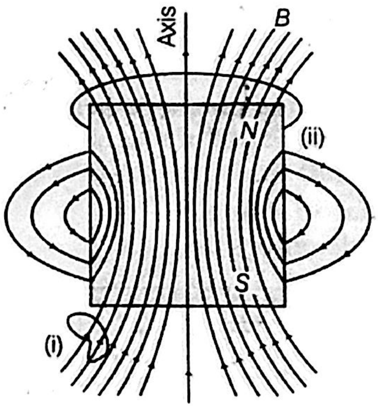
or

$$\boxed{\mathbf{F} = \frac{\mu_0}{4\pi}\cdot\frac{m_1 m_2}{r^2}} \qquad \left[\because k = \frac{\mu_0}{4\pi}\right]$$

where, m_1 and m_2 are magnetic strength of poles and k is magnetic force constant. Its SI unit is A-m.

1.2 Magnetic Field Lines

These are imaginary lines which give pictorial representation for the magnetic field inside and around the magnet.



Their properties are given as below:

(i) These lines form continuous closed loops.

(ii) The tangent to the field line at a particular point gives the direction of the field at that point.

(iii) Larger the density of the lines, stronger will be the magnetic field.

(iv) These lines do not intersect one another.

1.3 Magnetic Dipole

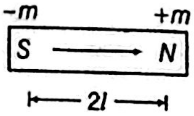
An arrangement of two equal and opposite magnetic poles separated by a small distance. e.g. A bar magnet.

Magnetic Dipole Moment (M)

It represents the strength of magnets. The magnetic dipole moment of a magnetic dipole is

given by $\boxed{\mathbf{M} = m \times 2l}$

where, m is pole strength and $2l$ is dipole length directed from S to N.



The SI unit of magnetic dipole moment is A-m^2 or J/T. It is a vector quantity and its direction is from South pole to North pole.

Magnetic field strength at a point due to a bar magnet at

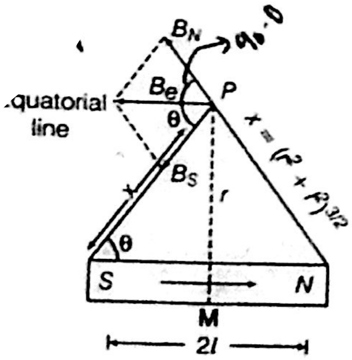
(i) **On axial line** (end-on-position)

$$\boxed{\mathbf{B}_a = \frac{\mu_0}{4\pi} \cdot \frac{2\mathbf{M}}{r^3}} \qquad (\because r >> l)$$

The direction of magnetic field is along the direction of magnetic dipole moment (M).

(ii) **On equatorial line** (broadside-on-position)

$$\boxed{\mathbf{B}_e = -\frac{\mu_0}{4\pi} \cdot \frac{\mathbf{M}}{r^3} = -\frac{\mu_0 \mathbf{M}}{4\pi r^3}}$$

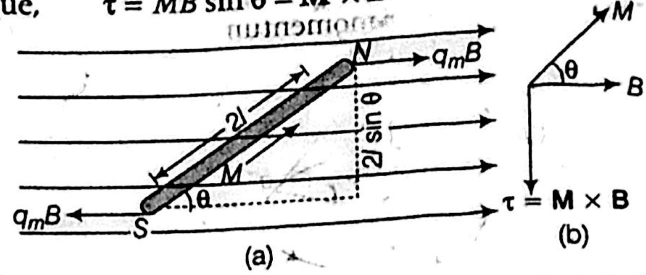


The direction of magnetic field is parallel to the magnetic dipole and opposite to the direction of dipole moment.

1 4 Torque on a Bar Magnet in a Uniform Magnetic Field

A uniform magnetic field **B** is represented by equidistant parallel lines, NS is a bar magnet of length $2l$ and strength of each pole is M.

Torque, $\tau = MB \sin\theta = \mathbf{M} \times \mathbf{B}$



where, θ is the angle between **M** and **B**. Its SI unit is joule per tesla (JT^{-1}).

$\tau_{max} = MB$, when dipole is perpendicular to the field and $\tau = 0$, when dipole is parallel or anti-parallel to the field.

Potential Energy of a Magnet Dipole (Bar Magnet) in a Magnetic field

Potential energy of a magnetic dipole in a magnetic field is given by

$$\boxed{U = -MB\cos\theta = -\mathbf{M} \cdot \mathbf{B}}$$

where, θ is the angle between **M** and **B**.

Work done in rotating the dipole in a uniform magnetic field from θ_1 to θ_2 is given by

$$W = MB(\cos\theta_1 - \cos\theta_2)$$

The direction of dipole moment can be obtained by right hand thumb rule. Its SI unit is A-m^2.

NOTE Current loop behaves like a magnetic dipole whose **dipole** moment is given by $M = IA$.

Oscillation of a Freely Suspended Magnet

The oscillations of a freely suspended magnet (magnetic dipole) in a uniform magnetic field are in SHM. The time period of oscillation,

$$\boxed{T = 2\pi\sqrt{I / MB}}$$

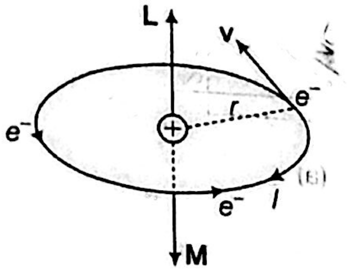
where, I = moment of inertia of the magnet,
M = magnetic moment
and B = magnetic field intensity.

1.5 Magnetic Dipole Moment

Magnetic dipole moment of a revolving electron is given by

$$M = \frac{evr}{2} \quad \text{or} \quad \boxed{M = \frac{e}{2m}L}$$

where, v is the speed of electron on a circular path of radius r. L is angular momentum and given as $L = mvr$.



Orbital magnetic moment of a revolving electron

1.6 Force Between two Magnetic Dipoles

Mutual force of interaction between two magnetic dipoles is given by

$$\boxed{F = \frac{\mu_0}{4\pi} \cdot \frac{6\,M_1 M_2}{r^4}}$$

where, M_1 and M_2 are magnetic dipole moments of two different magnets.

Bar Magnet as an Equivalent Solenoid

The expression of magnetic field at distance r from centre is given by

$$\boxed{\mathbf{B} = \frac{\mu_0}{4\pi} \cdot \frac{2\mathbf{M}}{r^3}}$$

This expression is equivalent to that of bar magnet.

1.7 The Electrostatic Analogue

The magnetic dipole is analogous to an electric dipole consisting of two equal charges of opposite sign ($\pm q$) seprated by a certain distance (**2a**). It has an electric dipole moment

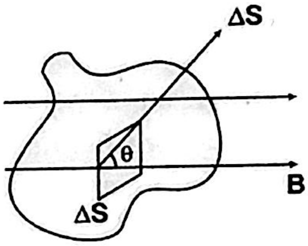
$$\boxed{\mathbf{p} = q(2\mathbf{a})}$$

The Dipole Analogy

Free Space Constant	**Electrostatics** ($1/\varepsilon_0$)	**Magnetism** (μ_0)
Dipole moment	$\mathbf{p}$	$\mathbf{M}$
Equatorial field for a short dipole	$-\mathbf{p}/4\pi\varepsilon_0 r^3$	$-\mu_0\mathbf{M}/4\pi r^3$
Axial field for a short dipole	$2\mathbf{p}/4\pi\varepsilon_0 r^3$	$\mu_0 2\mathbf{M}/4\pi r^3$
External field : Torque	$\mathbf{p} \times \mathbf{E}$	$\mathbf{M} \times \mathbf{B}$
External field : Energy	$-\mathbf{p} \cdot \mathbf{E}$	$-\mathbf{M} \cdot \mathbf{B}$

Magnetism and Gauss' Law

The net magnetic flux (ϕ_B) through any closed surface is always zero.



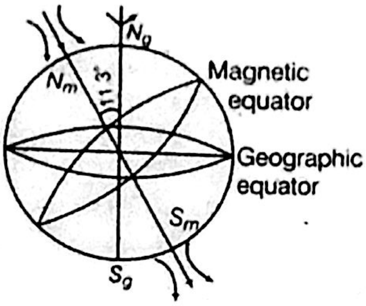
This law suggests that the number of magnetic field lines leaving any closed surface is always equal to the number of magnetic field lines entering it.

$$\boxed{\phi_B = \Sigma \mathbf{B} \cdot \Delta\mathbf{S} = 0 = \oint_S \mathbf{B} \cdot \Delta\mathbf{S} = 0}$$

[TOPIC 2] Earth's Magnetism and Magnetic Properties of Materials

2.1 Earth as a Magnet

Earth behaves like a magnet whose North pole is somewhere close to geographical South pole and magnetic South pole is closed to geographical North pole.



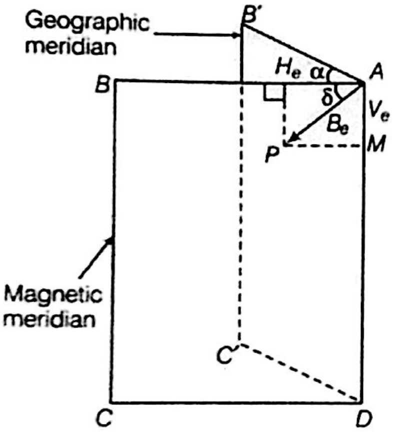
In outer core of the earth iron, nickel and small quantities of other metals are present in molten form and flow in a defined path. This flow of liquid iron and other metals generate electric currents, which in turn produce magnetic fields.

2.2 Magnetic Elements

There are three elements of the earth's magnetic field namely

(i) The angle between geographical meridian and magnetic meridian at a place is known as **angle of declination** (α).

(ii) **Magnetic Inclination or Dip** In magnetic meridian, the angle made by direction of the earth's total magnetic field (B_e) with the horizontal is known as dip (δ).



(iii) **Horizontal Component of the Earth's Magnetic Field** It is the component of the earth's total magnetic field along the horizontal direction.

$$H_e = B_e \cos \delta$$

- Relationship between horizontal and vertical components of the earth's magnetic field and angle of dip is given by

$$H_e = B_e \cos \delta$$

and $$V_e = B_e \sin \delta$$

∴ $$V_e / H_e = \tan \delta$$

Various Terms Related to Magnetism

Magnetic Intensity (H)

The capability of magnetic field to magnetise the substance is measured in terms of magnetic intensity of the field.

$$\boxed{\mathbf{B} = \frac{\mathbf{B_0}}{\mu_0}}$$

where, B_0 = magnetic field inside vacuum and

$\mu_0 = 4\pi \times 10^{-7}\ \text{T-mA}^{-1}$.

Its SI unit is A m^{-1}.

Intensity of Magnetisation (I)

The magnetic dipole moment induced per unit volume in the magnetic material due to magnetising field is known as intensity of magnetisation.

$$\boxed{\mathbf{I} = \mathbf{M}/V = m/A}$$

where, M = induced magnetic dipole moment,

m = pole strength,

V = volume of specimen

and A = cross-sectional area.

Magnetic Permeability (μ)

It is equal to the ratio of magnetic induction to intensity of magnetising field.

$$\boxed{\mu = \frac{\mathbf{B}}{\mathbf{H}}}$$

Magnetic Susceptibility (χ_m) It is equal to the ratio of intensity of magnetisation and magnetising field

$$\boxed{\chi_m = \frac{I}{H}}$$

It has no unit. It is a scalar quantity.

Magnetic Induction (B)

It is defined as the total number of magnetic lines of force crossing per unit area through the magnetic material.

$$\boxed{B = \mu_0 (H + I) = \mu_0 H(1 + \chi_m)}$$

where, μ_0 = permeability of free space,
H = magnetising field
and I = intensity of magnetisation.

The SI unit of magnetic induction is Tesla(T) or Wbm^{-2} which is equivalent to $\text{Nm}^{-1}\text{A}^{-1}$ or $\text{JA}^{-1}\text{m}^{-2}$.

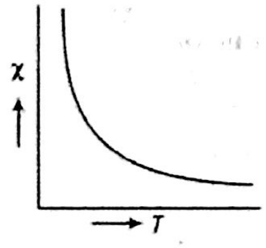
2.3 Classification of Magnetic substance

On the basis of mutual interactions or their behaviours, *the magnetic materials placed in a uniform magnetic field are classified into three parts*

(i) Paramagnetic substance
(ii) Diamagnetic substance
(iii) Ferromagnetic substance

Property	Paramagnetic substance	Diamagnetic substance	Ferromagnetic substance
When placed in a uniform magnetic field	Feebly magnetise along applied field	Feebly magnetise opposite to magnetic field or repelled by magnets	Strongly magnetise along magnetic field
Susceptibility (χ_m)	Small and positive $0 < \chi_m < \varepsilon$, ε = small number	Small and negative $-1 < \chi_m < 0$	Very large $\chi_m > 1000$
Relative permeability	$1 < \mu_r < 1 + \varepsilon$ ε = small number	Positive and less than one $0 < \mu_r < 1$	Large value $\mu_r > 1000$
Effect of temperature	$\chi_m \propto \frac{1}{T}$	Independent with temperature	$\chi_m \propto \frac{1}{T - T_C} (T > T_C)$
Variation of I with H	Linearly change	Linear change and saturable low temperature	Non-linear change and ultimately attains saturation
In a non-uniform magnetic field	Tends to move from weaker to stronger magnetic field	Tends to move from stronger to weaker magnetic field	Tends to move quickly from weaker to stronger magnetic field
Examples	Pb, H_2O, NaCl, Bi, Cu, Si, Sb	Na, Ca, O_2, $CuCl_2$, Al	Ni, Co, Fe, Fe_2O_3, Gd

Curie Law



It states that the magnetic susceptibility of paramagnetic substances is inversely proportional to the absolute temperature, i.e.

$$\chi \propto 1/T$$

For paramagnetic material,

$$\boxed{\chi = C/T} \quad [C = \text{Curie constant}]$$

Curie Temperature

With the rise of temperature, susceptibility of ferromagnetic materials decreases. At a certain temperature, ferromagnetic pass over to paramagnetic. This transition temperature called Curie temperature.

Curie-Weiss Law

This describes the magnetic susceptibility χ_m of a ferromagnet in the paramagnetic region above the Curie point. It is expressed as

$$\boxed{\chi_m = C / (T - T_C)} \qquad [\because T > T_C]$$

where, C is called Curie's constant, T is an absolute temperature in kelvin and T_C is Curie temperature.

2.4 Permanent Magnets and Electromagnets

The substances which are at room temperature retain their ferromagnetic property for a long period of time are called **permanent magnet**. Permanent magnet can be made by placing a rod of ferromagnetic material in a current carrying solenoid. The magnetic field of the solenoid magnetises the rod.

The material used for making permanent magnet should have high retentivity, so that the magnetisation is strong and high coercivity so that the magnetisation is not erased by stray magnetic field/temperature fluctuations or minor mechanical damage. Steel is favoured for making permanent magnet.

- Steel possesses high coercivity, hysteresis loss, moderate permeability, susceptibility and high retentivity, therefore it is fit for making permanent magnet.
- On placing a soft iron rod in a current carring solenoid the magnetism of the solenoid increases by thousands folds. On switching off the current flowing through solenoid the magnetism is effectively switched off. It is because the soft iron core has a low retentivity. Some suitable materials for making permanent magnets are alnico, cobalt, steel and ticonal.
- Soft iron possesses high permeability, susceptibility and low retentivity and low coercivity and low hysteresis loss, therefore it is fit for making **electromagnet.**